2019-10-15

Hospital Ward Temperatures Related to Hypothermic Risk in Orthopaedic Patients

Goodhew, Steve

http://hdl.handle.net/10026.1/14934

10.1080/09613218.2019.1674627
Building Research and Information: the international journal of research, development and demonstration
Taylor & Francis (Routledge)

Hospital Ward Temperatures Related to Hypothermic Risk in Orthopaedic Patients.

Goodhew S[a]; Latour J.M[b,c]; Duthie J[c]; Shirreff H[c]; Riddlestone P[c]; Metcalfe J[c] Fox, M[a]

Journal name: Building, Research & Information

Acceptance date: 17th September 2019

[a] School of Art, Design and Architecture, Faculty Art and Humanities

University of Plymouth, United Kingdom

[b] School of Nursing and Midwifery, Faculty of Health and Human Science, University of Plymouth, Drake Circus, Plymouth, Devon, PL4 8AA, United Kingdom

[c] Department of Trauma and Orthopaedics, University Hospitals Plymouth NHS Trust, Plymouth, United Kingdom

Corresponding Author: Steve Goodhew

School of Art, Design and Architecture, Faculty Art and Humanities

University of Plymouth

Room 116, Roland Levinsky Building, Drake Circus, Plymouth, Devon, PL4 8AA,

Email: s.goodhew@plymouth.ac.uk

Phone number: +44 1752 852199

Jos Latour (b,c) email: jos.latour@plymouth.ac.uk

James Metcalfe (c) email: jamesmetcalfe@nhs.net

Joanna Duthie (c) email: joannaduthie@nhs.net

Henry Shirreff (c) email: henry.shirreff@nhs.net

Peter Riddlestone (c) email: peter.riddlestone@nhs.net

Matthew Fox (a) email matthewfox4@plymouth.ac.uk

Acknowledgements

The University of Plymouth Sustainability Institute has funded this project.

Declaration Of Interest

The authors declare no conflict of interest.

Hospital Ward Temperatures Related to Hypothermic Risk in Orthopaedic Patients.

ABSTRACT

This paper presents an exploration of the relationship between ward air temperature, radiative effects and hypothermic risk in elderly male orthopaedic patients admitted to a clinical ward in a university hospital. Five beds spaces have their air temperature measured alongside appropriately chosen periods of time-lapse thermography used to assess the probably mean radiative influences. Associated patient clinical data was compared with the environmental data. Because patient core temperatures were measured at different periods throughout the day, this resulted in analysis on an averaging basis allowing for trends to be identified. It was possible to identify which bed spaces with the associated patient characteristics and thermal environment were likely to influence lower than expected patient core temperatures. In conclusion this study resulted in a null hypothesis based on the measured data and research parameters as no significant correlation between patient core body temperature and indoor air temperature could be deduced. However, this study has established a new methodology for monitoring hospital ward environments.

Keywords: Hospital building; indoor thermal environment; thermography; patients; ward.

Introduction

Thermoregulation is the physical process of a maintaining constant core body temperature in human bodies. Humans normally maintain a body temperature at around 37°C, and preserving this relatively high temperature is critical to human survival (Tansey and Johnson, 2015). Temperature in mammals will vary diurnally within a narrow range and temperatures outside this can have a profound effect at both a biological and clinical level (Faulds and Meekings, 2013).

Maintenance of normal temperature prior to and during surgery is essential for good patient outcomes (Insler and Sessler, 2006). Patient responses to ambient temperatures can lead to changes in core temperature adversely affecting surgical outcomes; ensuring patients are sufficiently warm preoperatively and perioperatively can reduce the risk of hypothermia.

According to the National Institute for Health and Care Excellence, Inadvertent Perioperative Hypothermia (IPH) is defined as patients having a core body temperature of below 36.0°C (NICE, 2018). Above this temperature, patients are classified as 'comfortably warm' during pre and postoperative phases with normal temperatures between 36.5°C and 37.5°C. IPH can lead to postponement of surgery or delay in recovery after surgery (Romanzini, Carvalho, & Galvão, 2015) with the potential of increased healthcare costs (Porthosp, 2012), anxiety levels of patients (Ivarsson, Kimblad, Sjöberg, & Larsson, 2002) and bed occupancies (Campbell, 2018).

The problem

Health service providers need to work towards low operative mortality rates and ensuring swift recovery periods whilst maintaining efficient use of operating facilities. In health the human body has both conscious and autonomic reflexes to maintain a stable core body temperature (CBT) in a wide range of environmental temperatures as well as the ability to modify the immediate environment to influence the impact of temperature on the body. In cases of illness, trauma or infirmity the body's ability to maintain homeostasis is impaired and therefore more susceptible to the environmental conditions. Patient hypothermia (core body temperature below 36^0C) can cause several complications in patients resulting in increased healthcare cost. The impact of hypothermia can also increase mortality, hospital length of stay, or admission to intensive care units due to decreased health conditions (NICE, 2007). Pre and perioperative hypothermia in patients have been investigated (Andrzejowski, Hoyle, Eapen, & Turnbull, 2008) along with associations of patient's morphometric characteristics and intraoperative core temperature changes (Kurz, Sessler, Narzt, Lenhardt, & Lackner, 1995). Proper thermal management may reduce complications and improve the outcome in high-risk surgical patients (Leslie and Sessler, 2003). It has been proposed that mild intraoperative hypothermia can prolong the duration of post-anaesthetic recovery (Lenhardt et al., 1997). One variable beyond those of illness, age, gender, and body mass index (BMI) that can impact on a preoperative patient is the thermal environment that patient experiences in the hours before an operation. Whilst direct interventions such as active patient warming (Torossian et al., 2016) are legitimate, a remediation would be preferable for hospital ward environments to support non-hypothermic pre-operative patients. There is a current debate over the importance of hospital refurbishments compared to building new (Sheth, Price, & Glass, 2010). Therefore, rigorous assessment of the internal environments of clinical wards spaces should be taken into account when (re)designing hospital building.

The UK Government has published guidance on the design of new hospital buildings (Department of Health, 2013, 2014). In Health Building Note 00-01 (2014), general guidance specifically relates to thermal comfort, suggesting minimising solar gains, providing summer cooling, maximising the use of natural ventilation and offering local control over heating. Health Building Note 00-03 (2013) outlines requirements for multi-bed rooms, which are to include provision for clinical and personal care, maximum bed numbers per room, space for procedures and privacy, sanitary and ablution provisions, social entertainment and comfort, and fire protection. Yet there is no direct requirement related to the internal thermal environment of any spaces. Whilst much of the design guidance focuses on thermal comfort, further work by the Department of Health (2015) on the adaption of hospital buildings to climate change recognises that 90% of hospitals are at risk of overheating, which can directly impact on patient health and mortality. This is likely to become more significant as temperatures rise through the next century.

What has been studied

The direct relationship between human core body temperatures and their surrounding thermal environment may not be best benchmarked via thermal comfort measurements. The most prevalent method of assessing many of the parameters that will impact on potential hypothermia is based on the thermal comfort related variables.

Of the methods used to assess thermal comfort, ASHRAE Standard 55 (ANSI/ASHRAE, 2004), BSI standard EN16798-1:2019 (BSI, 2019), and ISO 7730 (ISO, 2005) are based on one of the most widely adopted models, the Fanger's comfort model (van Hoof, 2008). Thermal comfort has been evaluated inside hospital buildings (Du, 2018; Hwang, Lin, Cheng, & Chien, 2007; Khalid, Zaki, Rijal, & Yakub, 2019; Khodakarami and Nasrollahi, 2012; Pourshaghaghy and Omidvari, 2012; Verheyen, Theys, Allonsius, & Descamps, 2011), staff related comfort, (Derks, Mishra, Loomans, & Kort, 2018; Hellgren, Eero, Lahtinen, Henri, & Reijula, 2008; Yau and Chew, 2009) alongside studies of the internal thermal environment of clinical spaces, (de Wilde and Coley, 2012; Del Ferraro, Iavicoli, Russo, & Molinaro, 2015; Lawrence, Jayabal, & Pattabi, 2018; Short, Lomas, Giridharan, & Fair, 2012; Skoog, Fransson, & Jagemar, 2005). However, few studies have investigated the impact of the ward's thermal environment directly upon the core body temperature of patients. Therefore, the aim of this study is to identify associations between patient core body temperature and the thermal hospital ward environment during winter and summer seasons. The study involves taking a series of air temperature measurements and thermographic images at 5 bed spaces and the surrounding ward spaces over winter and summer periods.

Material and Methods

When conducting temperature and thermal comfort monitoring of existing buildings, it is commonplace to use multiple strands of equipment and methodologies, such as used in co-heating testing with ventilation rates, CO2 concentrations, latent influences, heat loss through fabric (Bauwens and Roels, 2014). However, an active hospital environment is quite a different prospect for temperature monitoring programs. There are ranges of limitations that constrain the ability to collect meaningful data. For example, patient confidentiality, multiple staff use of space leading to a lack of familiarisation with measurement devices placed in ward area. These issues are also compounded by the need not to obstruct access to vital medical equipment and the requirements for good hygiene and not impeding a high degree of cleanliness. These requirements contribute to the need to produce a methodology that enables the environment to be monitored whilst maintaining patient confidentiality and appropriate patient core body temperatures to be established within different internal zones. Whilst infrared imaging is not ideal for Mean Radiant Temperature (MRT) measurement in all spaces, time-lapse thermal imaging offers a qualitative assessment of apparent MRTs.

This technique was combined with WIFI connected patient space air temperature measurements and patient core body temperatures.

To investigate the relationship between hypothermic risk in orthopaedic patients and the air temperature of the hospital setting, a study was conducted over a one-year period on a single male 5-bedded bay within a ward at the hospital. Seeking to refine the data, two specific periods of two months were focused upon for analysis. These were selected based on the warmest and coolest months within the investigated year. The two periods spanned from:

- 28th May to 27th July, which was the warmest period during the study.
- 8th December to 7th February, which was the coolest period during the study.

Within these periods, two aspects were monitored. The first was temperature monitoring, which comprised of external air temperature monitoring, bed space air temperature monitoring and patient core body temperature. The second was time-lapse thermal imaging, which observed the radiant temperature changes from the surfaces of the patients' bed spaces. By monitoring each of these aspects, it was possible to ascertain whether the surrounding environment directly influences patients' core body temperatures in a hospital clinical ward.

Case study bay

The study centred on a single bay of elderly (>65 years of age) male orthopaedic patients. Many of these patients had suffered from hip fractures and so have reduced mobility both pre and post op mostly confining them to their bed space area. The cognitive status of some of the patients may also impair their ability to influence their environment to self regulate their CBT for example, asking for a blanket if feeling cold.

The bay was located within an orthopaedic patient ward located on the 11th floor of the main hospital building. Within the bay being investigated, there were five beds and one office desk. Figure 1 presents a plan and elevation, which illustrates the ward environment. Patients in this bay were admitted for pre and postoperative care.

The hospital was completed in 1981 and is centred on a large pre-cast concrete framed building, which rises to 12 storeys and has large single glazed windows. The bay being investigated is approximately 45 square meters with one external wall that faces east. Within this external wall are two windows, which can be opened by staff or patients. The windows have internal blinds (Figure 2). Below each window is a double radiator, which is controlled via a hospital wide central management system. On the opposite side of the bay to the external wall is the main ward corridor, which leads directly to the nurse’s station and entrance to the ward.

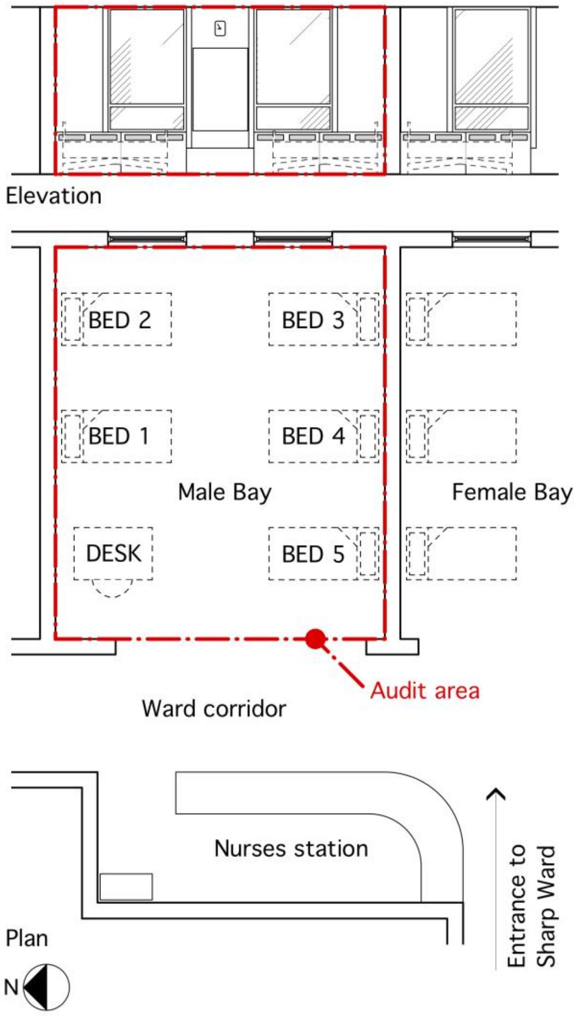
Elevation
BED 2
BED 3
BED 1
BED 4
Male Bay
Female Bay
DESK
BED 5
Audit area
Ward corridor
Nurses station
Entrance to Sharp Ward
Plan
N

Figure 1

Figure 2

Temperature monitoring

Three aspects of temperature monitoring were undertaken as part of this study. Internal and external air temperature monitoring, and patient core body temperature monitoring. Date and time stamps were taken for each measurement, so that direct comparisons could be made between data sets.

External air temperature monitoring

External air temperature monitoring was collected by a weather station, which was located on the roof of the hospital building, two floors above the study bay. Data from this device was set to collect measurements every one-minute and was retrieved remotely using the online service ‘Skylink Pro’ (Skyview, 2018), which collected the data.

In addition to enabling comparisons with internal air temperatures and core body temperatures, the data from the external weather station was used to help inform the focus periods.

Internal air temperature monitoring

Internal air temperature monitoring was collected via five strategically located data loggers. The data loggers used were Onset Hobo MX1101 devices (Onset, 2015), which allowed discreet positioning, and Bluetooth data collection that made possible to download data without disturbing patients. Loggers were programmed to collect air temperature data every 15 minutes. The accuracy of the data loggers is at ±0.21^{o}C when measured from between a range of 0^{o}C to 50^{o}C.

To offer a good comparison with patient core body temperatures, the data loggers were located immediately adjacent to each bed space in the bay and as close to patient body level as practically possible whilst minimising the treat of being moved or damaged by patient or staff activities. Figure 3 shows one of the data loggers located next to a patient bed. Data was downloaded every two months to monitor the status of the loggers.

Figure 3

The data from the weather station and data loggers was analysed to determine the warmest and coolest two-month periods from the data set. This was necessary to gain clarity from overall year-long data set. To help further refine the data, internal and external air temperatures were averaged over two specific two-hour long periods within a day. These were from 05:30 to 07:30 and from 20:30 to 22:30. These times were selected to correspond with the times that patient core body temperatures were recorded by hospital staff.

Patient core body temperature monitoring

The measurement and documentation of patient CBT is part of routine clinical assessment of inpatients in the hospital setting. The CBT is derived from tympanic membrane temperature measured using a non-invasive thermometer, Braun Welsh Allen *ThermoScan* Pro 6000. In the patient group studied these observations are made three times a day as standard practice. Temperature measurements are recorded before breakfast at 8am, around midday and in the evening. Within the study group there was no change in the frequency, documentation or method of measurement. Within the selected time periods over 90% of the patients' CBT were recorded within the 2 hour time periods of 05:30 – 07:30 and 20:30 – 22:30.

Time-lapse thermography

To supplement the findings from the air temperature monitoring, a further investigation was conducted using thermography to observe the emitted radiant temperature from the surrounding built environment. Thermal imaging is a real-time and non-destructive method for viewing infrared radiation emitted from the surface of viewed objects using a thermal camera. From this infrared radiation the thermal camera is able to calculate an apparent surface temperature (Hart, 1990).

Whilst traditional methods of capturing single thermal images offer a snapshot of what the surface temperature of a piece of building fabric might be at one moment in time, often the effects from external and internal influences such as air temperature changes and solar gains can be missed or misinterpreted. This is often due to the length of time these influences take to manifest or perform. Time-lapse thermography is a lengthier method, which enables a series of thermal images to be compared sequentially to enable improved analysis and understanding of transient changes in the building fabric. For this study, a FLIR T620bx thermal camera (FLIR, 2013) was left in place for a 24-hour period from 23rd March at 16:00 to 24th March at 16:00.

The methodology established by Fox et al. (Fox, Coley, Goodhew, & Wilde, 2015) was used to conduct the investigation, with thermal images captured every 5 minutes. To gain the widest view of the bay possible, the thermal camera was located in an inaccessible position within the nurse's station and angled to face the external wall. The distance from the thermal camera to the external wall was approximately 12 meters. The data from this investigation was analysed using qualitative methods of image comparison (Walker, 2004), where image patterns were reviewed over the monitoring period and quantitative methods of surface temperature measurement, whereby the emissivity was measured (Avdelidis and Moropoulou, 2003). Once the investigation had been completed, the thermal images were assessed using FLIR ThermaCAM Researcher Pro software (FLIR, 2004), which enabled image adjustment, so that each image could be compared sequentially.

Statistical Analysis

Data are presented in mean, standard deviation, standard error, sample variance, and median formulated in MS Excel using descriptive analysis under the analysis ToolPack. Box and whisker plot diagrams were used to assess the spread of measured values over a mean, median and percentile distribution. Whiskers to the plot informed the extent of the maximum and minimum outliers. Scatter plots were overlaid to help represent the collected data from each measurement.

Ethical considerations

The study protocol was reviewed and approved by the Clinical Audit & Service Evaluation team of the University Hospitals Plymouth. A participant information sheet was developed and provided to patients and clinical staff to inform the study aims and to ensure transparency of the anonymously collected measurements. Furthermore, the study protocol was also reviewed and approved by the Arts and Humanities Research Ethics Sub-committee of the University of Plymouth.

Results

Temperature analysis

Core body temperature (CBT), bed space air temperature (BST) and external air temperatures (EAT) were collected over two specific periods. These periods were defined as being the coolest and warmest average month-long phases, when taking an average of the EAT during both the morning (05:30 – 07:30) and evening (20:30 – 22:30) measurement periods. During the coolest period, the average EAT was 8.2^{o}C and during the warmest period, the average EAT was 14.5^{o}C.

Having established the coolest and warmest periods, the first assessment was to observe the internal BST. For both of these periods, the average BST for all of the beds combined was observed to be relatively stable, fluctuating by about 2^{o}C between 23^{o}C to 25^{o}C during the measurement phase. However, when inspected on an individual bed basis, there appeared to be some disparity in the mean BST. The results of this are presented in Figure 4 (cool period) and Figure 5 (warm period).

For the cool period, the mean BST for the two beds nearest the external wall and windows (bed spaces 2 and 3) was 22.8^{o}C, and lower in comparison with those not immediately adjacent to the window in bed spaces 1, 4 and 5, where the average BST was around 23.5°C. For the warm period, a similar pattern was observed, though bed space 3, which was located on the southern side of the bay, was lower (24.3°C) than bed space 2 (24.6°C), which was on the northern side of the bay.

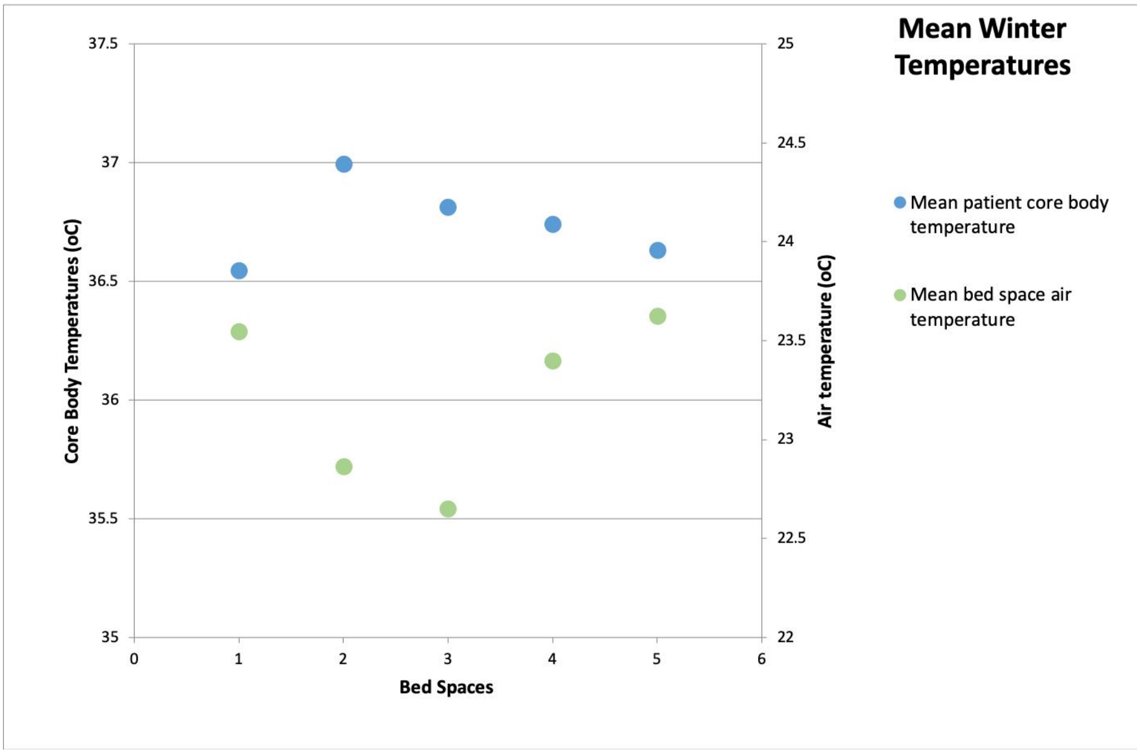

Figure 4

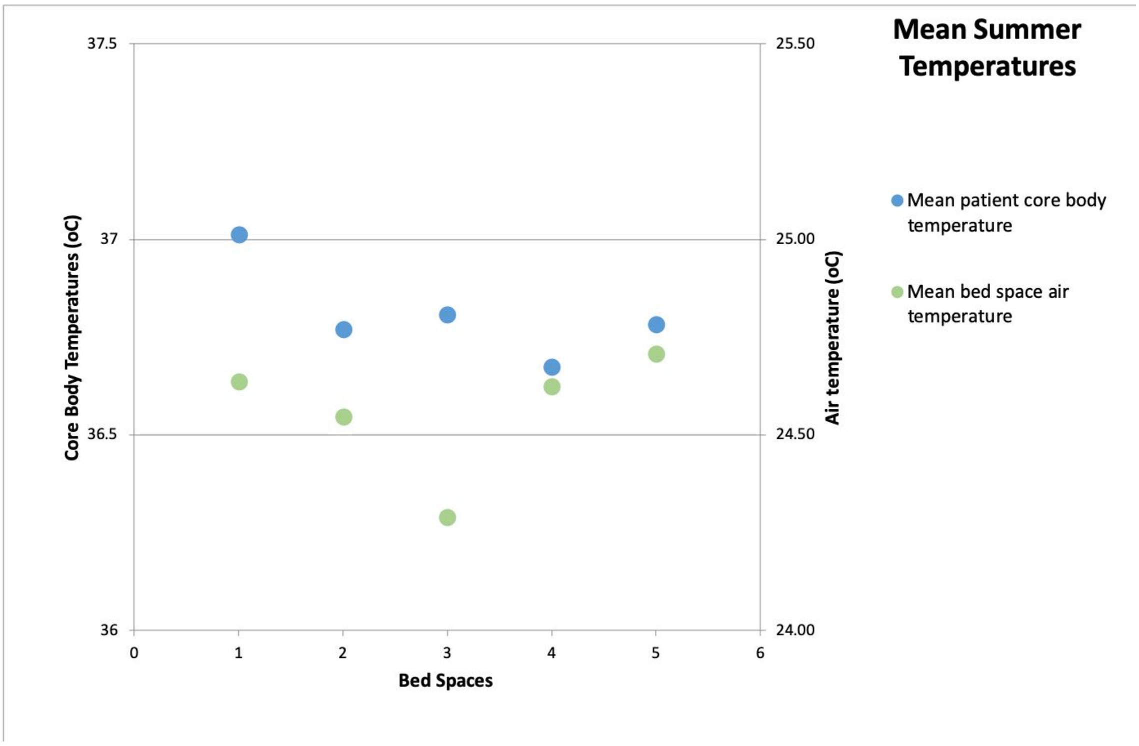

Figure 5

Figures 4 and 5 also present average CBTs for the 5 bed spaces. Plotted alongside the average BST enables comparisons to be made. During the cooler period, the average patient CBT in bed spaces 2 and 3 were higher than those in the other beds. Patients in bed space 1 had on average the lowest CBT. During the warmer period, the average CBT was highest in bed space 1, with the lowest CBT found in bed 4. Making comparisons between the average BST and the CBT revealed no direct correlations in the data.

Looking in greater detail at the data, Figures 6 (cool) and 7 (warm) present the entire measured patient CBT over the total study duration plotted against the average BST for all five beds. For both data periods, the occasions when a patient's CBT dropped below the 36^{o}C threshold appeared to have occurred during the warmest periods of the ward's average air temperature. In some limited cases this could be explained by interventions by staff or visitors affecting patient's environment e.g.

removing blankets or using table fans if the staff or visitor thought that the internal environment was subjectively warm but the patient may be unable to communicate feeling cold. During the cool period there were 33 instances of a patient CBT at 36°C or below. In the warm period the number of CBT measurements of 36°C or below were 35. The data presented in Figures 6 and 7 did not show a direct correlation between CBT and BST.

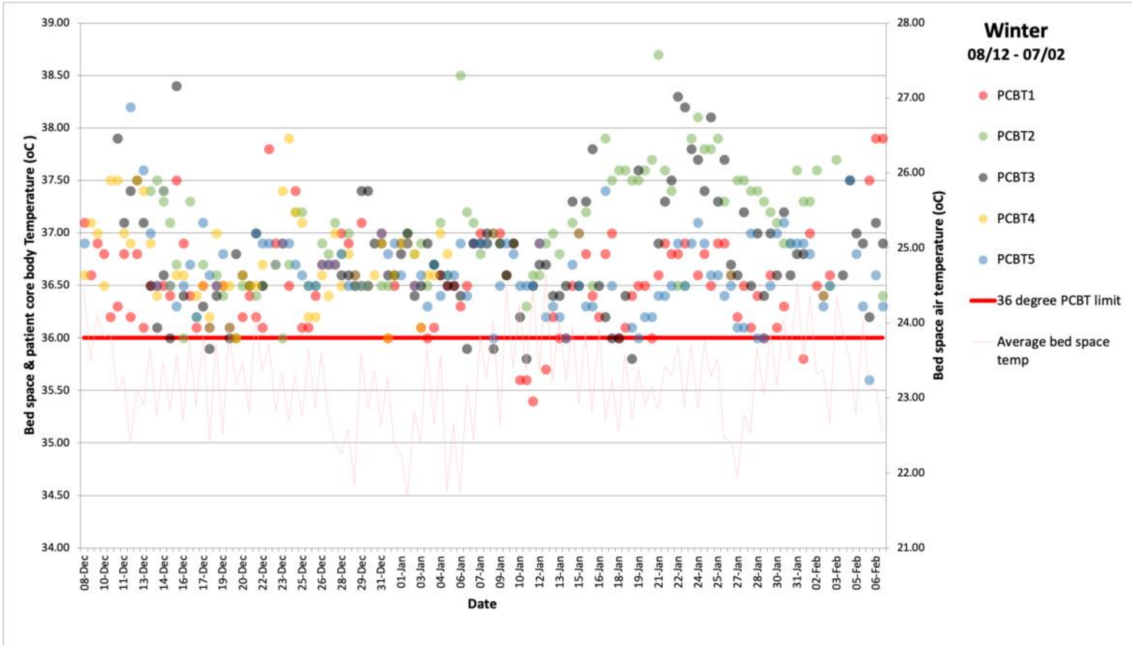

Figure 6

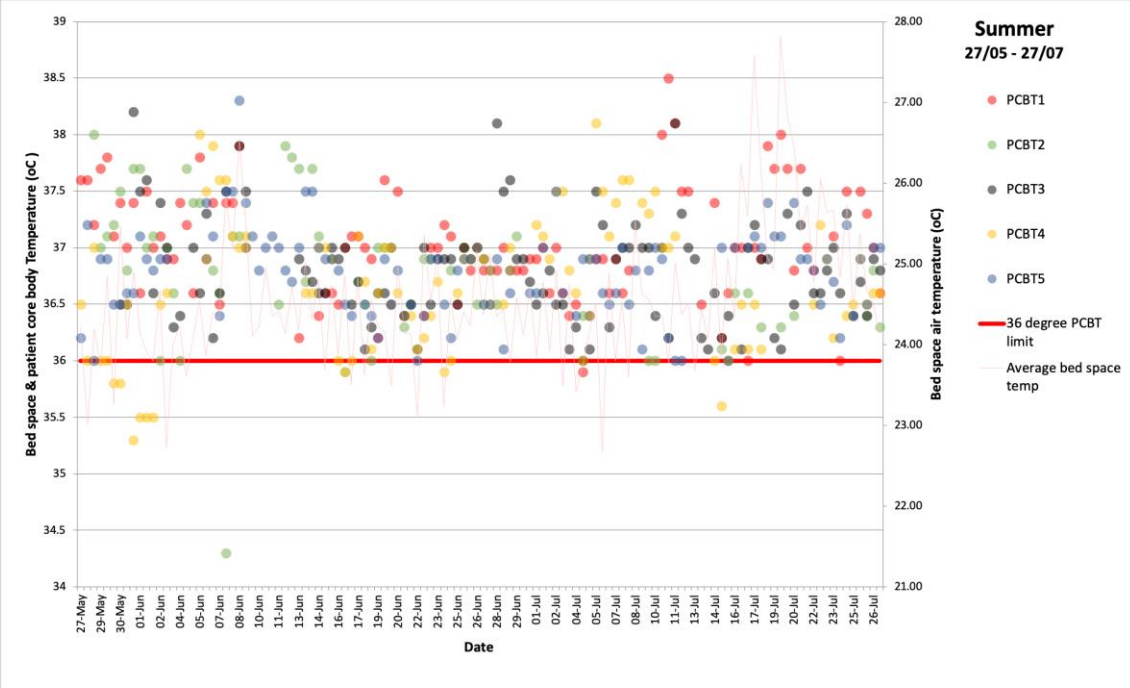

Figure 7

Further analysis of the data was undertaken to specifically inspect trends in patient CBT between different bed spaces independent of BST. To do this a box and whiskers method of graphical analysis was used, where the median, 75th and 25th percentiles were determined along with the maximum and minimum temperature outliers. The results from these are presented in Figure 8 (cool period) and Figure 9 (warm period). These figures illustrate the number of patients and their measured CBT in relation to the 36^{o}C threshold for surgery (NICE, 2018). During the cooler period, patients in bed space 1 appeared closer to the 36^{o}C threshold than those in other bed spaces. Whilst the average BST for this bed was one of the highest of the 5 beds, it is likely that something else is leading to this pattern in patient CBT. Also of interest is the observation that the average and upper 75th percentile of patients had a higher CBT in bed spaces 2 and 3, nearest the window and radiators compared with those in the other beds.

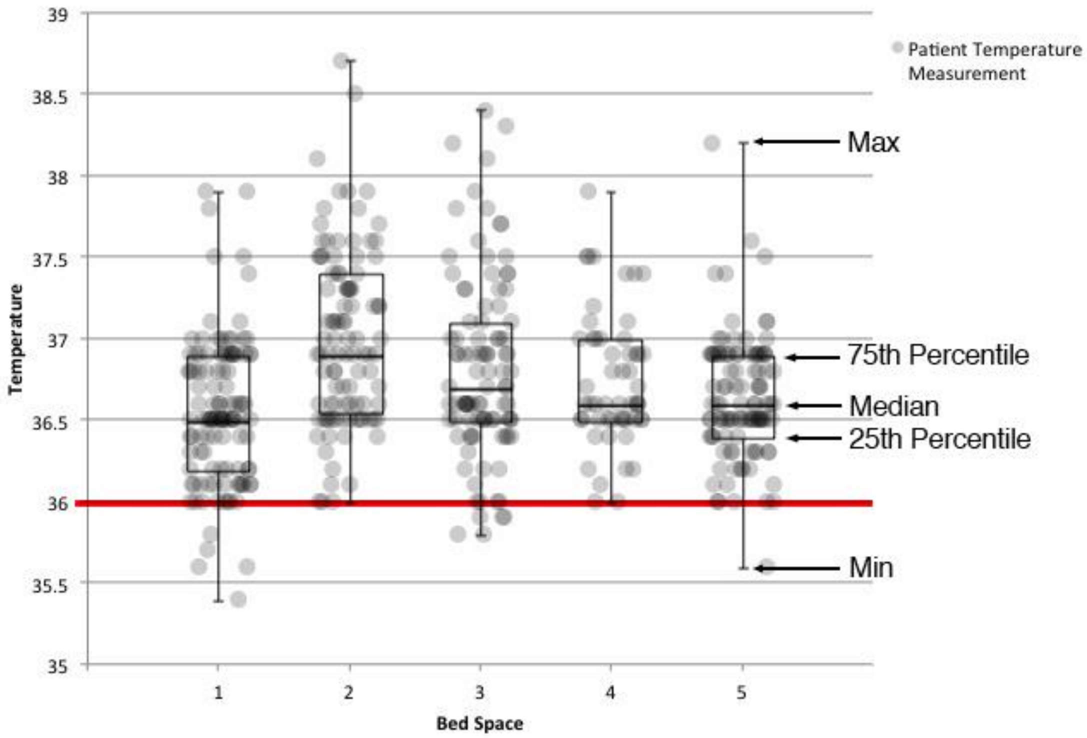

Figure 8

During the warm period it was interesting to notice that patients in bed spaces 1 and 2 had a higher measured CBT than those in the other three beds. This was particularly noticeable in bed space 1. Of all the bed spaces in the warm period, bed space 4 experienced the greatest number of patients falling below the 36°C CBT threshold with those in bed spaces 3 and 5 also presenting a high number of patients close to the 36°C CBT threshold.

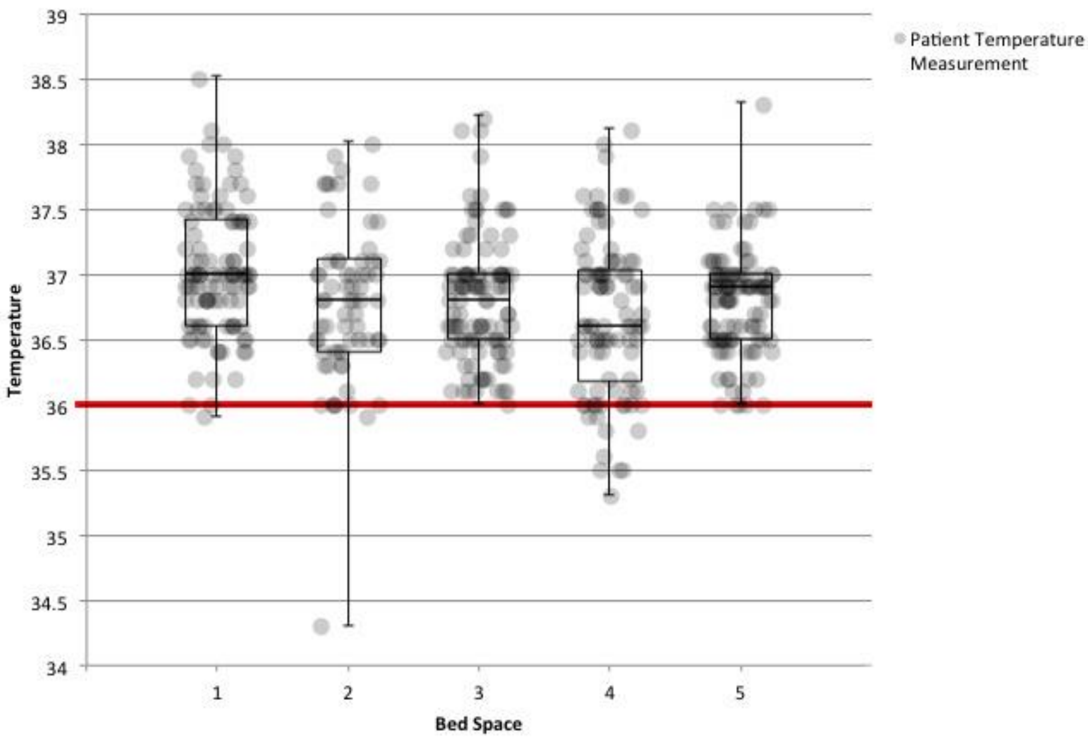

Figure 9

Thermal imaging results

Time-lapse thermal imaging resulted in 288 thermal images spaced every 5 minutes over a 24-hour period. All images were adjusted to contain a temperature span of between 20°C and 30°C. A selection of images at 3-hour intervals is presented in Figure 10.

Initial analysis made use of qualitative methods of image comparison. From reviewing the thermal images, it was clear from the appearance of the furniture and internal bulkhead (top of thermal image) that there was little change in apparent atmospheric temperature during the study. However, the two large external facing single glazed windows appeared much cooler than the surrounding built environment. This temperature appeared to remain uniform throughout the study. To further analyse the thermal images, it was necessary for quantitative analysis to be conducted.

Whilst there are many limitations to quantitative analysis using thermal imaging such as emissivity variations and distance from the thermal camera to the surface (Walker, 2004), it is possible to conduct simple surface temperature measurement using this technology. However, these surface temperatures can only be viewed as apparent to the thermal camera and might differ from actual temperatures due to limitations.

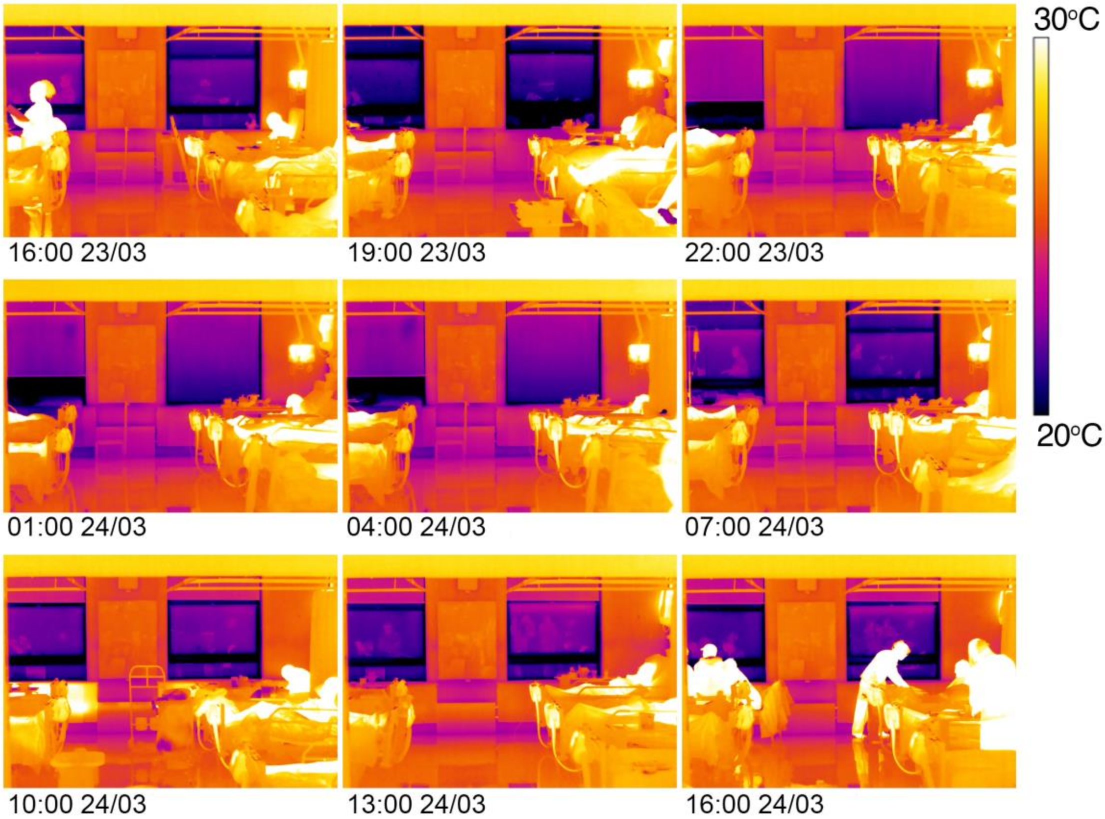

Figure 10

There were three features that were commonly viewed by the thermal camera during the 24-hour time-lapse period and permitted continuous quantitative analysis. First, the foreground bulkhead (top of the thermal image) measured emissivity (ITC, 2006) of 0.93. This would give an indication of the room atmospheric temperature. Second, the external wall (between the two windows) measured emissivity of 0.92. Third, the window blinds. The fabric blinds were drawn over the window during the night. Although mainly drawn closed, during the day the blind was still visible at the top of the window. Since the surface of the blinds had a measured emissivity of 0.85, it was possible to measure the apparent surface temperature throughout the 24-hour period. Being very thin in construction and close to the external window, this fabric would take on the atmospheric temperature immediately adjacent to the window, thereby giving a good indication of apparent radiant temperature from the large single glazed windows.

The results from the quantitative analysis during the 24-hour time-lapse thermal imaging are presented in Figure 11. This box and whisker plot shows that there was greater variation with the blind apparent surface temperature than from the foreground bulkhead apparent surface temperature.

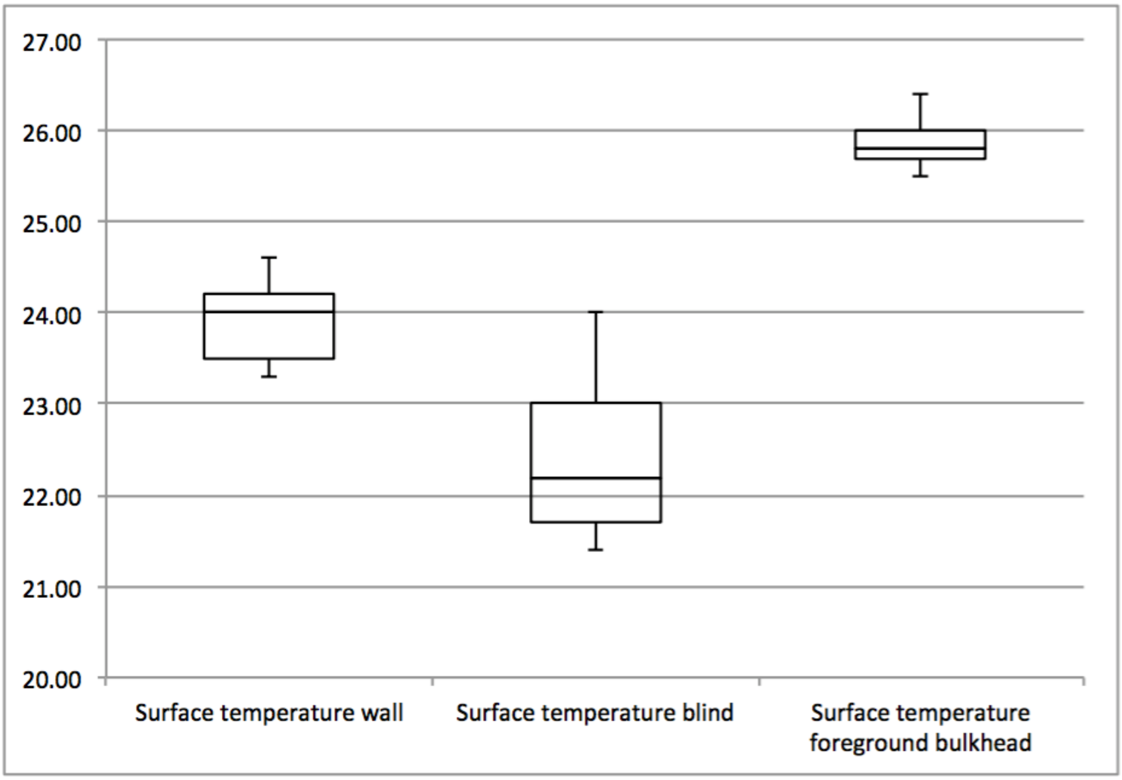

Figure 11

Findings from thermal imaging:

(1) The bulkhead spot temperature did not fluctuate very much during the 24-hour period and it measured an average air temperature of 25.7^{o}C. Although higher than the measured internal air temperature, the observed stability correlates with findings from the BST monitoring, where the internal air temperature fluctuated by only around 2^{o}C over the entire month long periods.

(2) The external wall surface temperature varied a little more than the bulkhead, though had an average surface temp of 24^{o}C. Subject to external conditions, this was expected to be more variable than the bulkhead measurements.

(3) The average temperature between the external wall temp and bulkhead temp is around 25^{o}C and aligns with the average air temperature readings recorded by the data loggers.

(4) The surface temp of the blind is at least 1.5^{o}C lower than that of the external wall surface temp, however, it fluctuates more significantly from a low of 21.5^{o}C to a high of 24^{o}C, which indicates that this element of construction is more responsive to environmental changes in temperature.

(5) Using qualitative analysis, it is apparent that the radiant temperature from the window area is much lower than that of its surroundings. This suggests that the radiant temperature could be having a cooling effect on patient CBT independent of the stable BST.

Discussion

Monitoring the hospital ward over two specific thermally diverse periods of time during a year has yielded interesting findings, which relate to the built environment, ward layout and its potential effect on patient CBT. Whilst during both the warm and cool periods it appears that the internal hospital temperature has limited direct relation or impact on patient CBT as discussed later in this section, there were bed spaces where a higher incidence of lower CBTs were recorded. The locations of these beds in a bay appear to have the potential to influence patient CBT.

Warm period

For the warm period, patient control and room layout in relation to solar orientation appeared to be the main drivers behind patient CBT. For instance, those patients who were located on the northern side of the room had on average higher CBT than those on the southern side of the room. This difference could result from patients on the northern side being subject to more direct solar gain than those on the southern side, who would have been out of direct solar gain.

Yet considering this closer, the patients with highest CBT during the warm period were located in bed space 1. Those in the next bed space along the northern side of the room had on average a lower CBT. One explanation for this could be that these patients had greater control over their environment by being located next to the openable window. Whilst this study did not monitor the instance of patients opening windows, it was observed on a number of occasions that the window would open a small amount to afford some ventilation. Those in bed space 1 not only lacked control over their environment, but were also subject to the greatest solar exposure, which could explain their increased average CBT.

With a lower average CBT in patients on the southern side of the room, it was interesting to observe that those in bed space 4 (directly opposite bed space 1) had the greatest number of patients falling below 36^{o}C CBT. Whilst they are out of direct solar exposure, it is not clear why this bed should have more patients at hypothermic risk compared with beds 3 and 5 either side. Though in beds 3 and 5, there were a high number of CBT measurements, which were close to the 36°C threshold in comparison with measurements taken on patients located on the northern side of the room.

Cool period

For the cool period, initial results showed that the average BST for the beds closest the windows were lower than beds not adjacent to the windows. However, comparisons with patient CBT did not correlate with these results, with average patient CBT being greatest in beds 2 and 3. Instead, patients in bed space 1 had the lowest average CBT. One explanation for the increased patient CBT in beds 2 and 3 could be their proximity to the radiators, which were located below the windows on the external wall. Whilst it is not clear why patients in bed space 1 have the lowest CBT, the fact that this bed yielded the highest patient CBT measurements during the warm period suggests that something about the location of the bed could also be impacting on these measurements during the cool period.

In addition to the CBT and BST monitoring, time-lapse thermal imaging was conducted for a 24-hour period. Three elements of the ward built environment were monitored using qualitative and quantitative analysis. An internal bulkhead wall, the external wall and a blind covering the external window. It was observed that the two external elements fluctuated in apparent temperature more than the internal bulkhead, with the blind being the lowest temperature of the three. Whilst not surprising, the qualitative images illustrate the cool radiant temperature emitted from the glazing into the room. This suggests that while the convective air temperature might remain stable in and around the ward and bed spaces (as observed from BST monitoring), the effects from radiant cooling could be having an impact on patient CBT, especially during the cool period, when the external air temperature might be having a greater impact on the single glazed windows than during the summer.

On this basis, bed 1 and beds 4 & 5 to a lesser extent, might have lower CBT readings because from cooler radiant temperatures from the single glazed window. Patients in beds 2 and 3 being closer to the window might be less affected due to their proximity to the radiators. From reviewing the thermal images using qualitative analysis it could be seen that the radiant temperature was greater when the blinds were drawn when compared to the exposed glazing, which appeared to have a lower radiant temperature, though the extent to which the blinds impacts on patient CBT was not clear from this study.

Summary of environmental monitoring

Until now, work by previous authors in the field of hospital monitoring has tended to focus on patient thermal comfort rather than patient health. Indeed design guidance from the Department of Health (2013, 2014) was found to relate more to comfort and function of wards. Yet, this research has found that whilst patients might feel a sense of comfort from their physical and thermal environment, clinical data comparisons with environmental monitoring data has shown great variances in CBT, which consequently has a direct impact on patient health. Whilst thermal comfort has a certain influence on patient health through reduced stress and wellbeing, few authors have made a direct correlation between the thermal environment and patient health through monitoring of CBT. This work therefore emphasises the importance of ward design, control and spatial arrangement for patient health pre and post operation.

Although hospital design guidance focuses on the delivery of new buildings, this work has underlined the challenges faced by much of the existing hospital building stock. With 90% of UK hospitals at risk from overheating, refurbishment is one strategy for minimising the negative effects from radiant cooling or overheating. Previous research into the refurbishment of hospital buildings considered methods for thermal improvement using natural, mechanical and shading systems (Short, et al., 2012). Yet such a program of physical refurbishment is likely to take time and resources to complete. Therefore, an intermediate strategy is required on existing hospital buildings to make them more resilient seasonal climatic changes. The findings from this study suggest that the location of the beds within the bay have the potential to influence patient CBT. Therefore, the location of patients immediately pre or post operation should be more carefully considered at different times of the year to help minimise the risk from low CBT and the associated problems this can lead to, such as hypothermia, cancelled operations or impeded recovery rates. This research therefore adds a new method for minimising the health risks to patients from low CBT resulting from a built environment that no longer performs as intended in a climate that is set to further change throughout the next decade (Department of Health, 2015).

It should be noted that whilst this study examined CBT, BST and infrared radiation, other factors might have impacted upon patient CBT that were not included in this analysis. Such factors include: patient illness, patient age and patient BMI. Furthermore, this research did not consider when windows were opened or blinds closed, nor when bed space curtains were drawn, all of which might have impacted on the results.

Reflection on methodology for assessing thermal conditions in hospital settings

It was recognised prior to the temperature audit that there would be numerous challenges limiting the ability to collect useful data for analysis between patient CBT and environmental conditions. For instance, there was a high level of sensitivity over collecting data whilst maintaining and reassuring patients of their confidentiality and privacy. Furthermore, monitoring in a live hospital environment meant that equipment needed to be located out of the way of vital medical equipment and staff operations. Challenges such as these acted to shape the design of the methodology for this study, where minimal intervention was chosen to monitor bed space temperatures.

The key to this methodology was to therefore collect data with the minimum of disruption. One example of this was the use of the thermal camera. For some building inspections, the application of mean radiant temperature (MRT) monitoring might prove useful in addition to air temperature monitoring. Yet MRT investigations involve invasive equipment, (Havenith, 2004) which needs to be specifically located in relation to the building fabric (Aparicio, Salmerón, Ruiz, Sanchez, & Brotas, 2016). Such equipment would either be obstructive to hospital activities or positioned to a corner of the room, where it would be ineffective at collecting valuable data. Whilst analysis of MRT might have yielded meaningful data during this study, it was not practical to monitor, and the thermal imaging therefore helped to visualise the apparent emitted infrared radiation, which might have been impacting on patient CBT.

This project has illustrated the benefit that thermal imaging on a time-lapse basis aids in monitoring the radiant heat over a prolonged period of time, thereby enabling the research team to understand patterns in behaviour, such as heating schedules. On the basis of this study, it might be useful to leave the thermal camera in place for a longer period of time, thereby capturing several heating cycles and changes in the way external climates (such as solar gain) impact upon the internal ward environment. However, as with the location of the BST loggers, it was important to locate the thermal camera in a discrete location, where it would not be moved or tampered with. This proved challenging. Locating the camera on a shelf with a view of the ward room provided a general overview of the room’s apparent infrared radiation, though image data was disrupted by bed space curtains being drawn, windows being opened or blinds being opened and closed. These uncontrollable aspects highlighted the difficulties in monitoring an active hospital ward, and motivated means to work within the parameters of the challenges.

Another challenge with the methodology was observed through the patient CBT monitoring. The nurses recorded these readings at different periods throughout the day, though not all at the same time. This made direct comparison between the data sets at specific times of day sometimes difficult and resulted in the analysis on a more averaging basis. Whilst this meant that specific features in a patient's environment were not observed, it did allow for trends to be more clearly identified.

Implications for clinical practice and building environment

Although the statistical significance of variation of temperatures (surface and body) has not been documented, the clinical significance is important to recognise because of the outliers where patients have very low body temperatures in relatively warm wards. Nurses and doctors need to monitor patients' core body temperatures on a regular basis and should consider taking measures to keep the body temperatures at a normal level. Further clinical investigations are needed to identify factors influencing patient body temperatures in clinical ward areas.

Building professionals and hospital maintenance teams are likely to be best served by liaising with clinicians concerning the particular requirements to the conditions related to patient temperatures and the influence on their recovery of health status.

Limitations

In addition to the limitations commonly encountered from monitoring data in a hospital setting, further limitations constrained this study. A limitation was the fact that only male patients were monitored. It is likely that female patients will have a different physiology to male patients and could have led to different results to those presented in this paper. Furthermore, the majority of patients observed were greater than 65 years of age, the patient's ability to affect their environment and/or ask for assistance if feeling too hot or too cold has not be taken into account with this analysis. Patients with full cognitive ability and communication will be able to control their immediate environment or request assistance, for example the removal or addition of blankets or clothing. A patient with cognitive impairment may be unable to express feeling cold in an otherwise warm environment, and thus clinical staff may not be alerted to potential hypothermia. This effect may explain the incidence of hypothermia when the air temperature in the ward is in the range of 23^{o}C to 22^{o}C, warmer than the reported ideal temperature range of 21.5^{o}C to 22^{o}C.

Age related health and wellbeing could have impacted upon the results, which for younger patients might have led to different results. The fact that only one ward was observed also led to a limitation. This was because other wards / rooms could not be audited to determine whether alternative layouts, solar orientation, built fabric or patient control caused different results to those published. Another limitation from this research centred around privacy and it was important to ensure thermal images and photos were recorded in a way that maintained patient anonymity. Finally, the ward has a patient-centred care approach leading to a flexible timing of measuring the core body temperatures. However, we were able to collect the patient's temperatures are two time slots a day, in the morning and evening.

Conclusion

This research compares ward environmental temperatures with patient CBT. Whilst previous research and design guidance has focused on thermal comfort as the driver for hospital design, this work highlights the negative impact that environment induced CBT can have on patient hypothermic risk. Findings found that optimal bed space positioning for pre and post-operative patients is variable according to the design of the hospital and the climatic condition. However, this work can suggest certain guidance for all situations, which can be used to supplement those documented in other literature and work towards minimising poor health resulting from a low CBT. These include:

- Controls. Thermal control should either be provided to all patients in the room or the design of the room should provide a thermal environment that does not unduly impact on the health of any patient.
- Design. Ward designs should not impose heavy loads such as high levels of internal passive solar gains or surfaces with lower temperatures than internal air temperatures.
- Spatial arrangement. Patient rooms should be designed so that pre and post-operative patients are located away from external influences such as radiative exchanges. There is currently no substantiated literature that provides advice to design teams on the siting of hospital beds that may contain pre-operative patients within a ward. This paper provides evidence on the importance of locating vulnerable patients in a room according to the climatic influences acting at the time.

Although thermal comfort can impact upon the health of patients, this study has shown that it is important to monitor patient CBT in addition. This is important, since the comfort and health of patients is not always connected, and in certain circumstances, more vulnerable patients may be subject to a greater impact from their environment without awareness.

In addition to the focus that hospital design guides have on new buildings, this work supplements work by others to provide methods for improving the health and wellbeing of patients in existing ageing hospital buildings, especially set against the context of a rapidly changing climate.

It should be noted that this study was limited in what could be investigated due to constraints expected from a hospital study. However, this work provides a methodology and foundation to future work, which could explore the themes of design, control and spatial arrangement on a larger scale.

Furthermore, whilst this paper focuses upon the core temperature of patients relative to their surrounding ward environment the thermal comfort of the staff also needs to be taken into account. It is therefore suggested that a study relating to the overall thermal comfort and activities of staff should be undertaken.

This paper does not analyse how patient factors affect the incidence of hypothermia and this warrants further investigation.

References

Andrzejowski, J., Hoyle, J., Eapen, G., & Turnbull, D. (2008). Effect of prewarming on post-induction core temperature and the incidence of inadvertent perioperative hypothermia in patients undergoing general anaesthesia. *British Journal of Anaesthesia*, *101*(5), pp. 627-631. doi:10.1093/bja/aen272 Retrieved from http://bja.oxfordjournals.org/content/101/5/627.abstract

ANSI/ASHRAE. (2004). Standard 55-2004: Thermal environmental conditions for human occupancy: American Society of Heating, Atlanta, Georgia: Refrigerating and Air-Conditioning Engineers

Aparicio, P., Salmerón, J. M. G., Ruiz, Á. A., Sanchez, F. J., & Brotas, L. (2016). *The globe thermometer in comfort and environmental studies in buildings.* SciELO, Chile.

Avdelidis, N. P., & Moropoulou, A. (2003). Emissivity considerations in building thermography. *Energy and Buildings, 35*(7), pp. 663-667. doi:10.1016/s0378-7788(02)00210-4 Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778802002104

Bauwens, G., & Roels, S. (2014). Co-heating test: A state-of-the-art. *Energy and Buildings, 82*, pp. 163-172. doi:https://doi.org/10.1016/j.enbuild.2014.04.039 Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778814003648

BSI. (2019). Energy performance of buildings. Ventilation for buildings. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Module M1-6 (Vol. BS EN 16798-1:2019): BSI.

Campbell, D. (2018, 4th Feb 2018). Hospitals cancelling urgent surgery despite NHS bosses' orders. *Guardian*. Retrieved from https://www.theguardian.com/society/2018/feb/04/hospitals-cancelling-urgent-surgery-despite-nhs-bosses-orders-england-cancer-heart-operations

de Wilde, P., & Coley, D. (2012). The implications of a changing climate for buildings. *Building and Environment, 55*(0), pp. 1-7. doi:10.1016/j.buildenv.2012.03.014 Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132312001060

Del Ferraro, S., Iavicoli, S., Russo, S., & Molinaro, V. (2015). A field study on thermal comfort in an Italian hospital considering differences in gender and age. *Applied Ergonomics, 50*, pp. 177-184. doi:https://doi.org/10.1016/j.apergo.2015.03.014 Retrieved from http://www.sciencedirect.com/science/article/pii/S0003687015000472

Department of Health. (2013). *Health Building Note 00-03: Clinical and clinical support spaces*. London: Crown copyright Retrieved from www.gov.uk/government/collections/health-building-notes-core-elements.

Department of Health. (2014). *Health Building Note 00-01: General design guidance for healthcare buildings*. London: Crown copyright Retrieved from www.gov.uk/government/collections/health-building-notes-core-elements.

Department of Health. (2015). *Health Technical Memorandum 07-02: EnCO2de 2015 – making energy work in healthcare*. London: Crown copyright Retrieved from www.gov.uk/government/collections/health-building-notes-core-elements.

Derks, M. T. H., Mishra, A. K., Loomans, M. G. L. C., & Kort, H. S. M. (2018). Understanding thermal comfort perception of nurses in a hospital ward work environment. *Building and Environment, 140*, pp. 119-127.

doi:https://doi.org/10.1016/j.buildenv.2018.05.039 Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132318303068

Du, B. Y. (2018). *A case study on thermal comfort in maternity hospital in Beijing* (MRes thesis. University of Nottingham.

Faulds, M., & Meekings, T. (2013). Temperature management in critically ill patients. *BJA Education, 13*(3), pp. 75-79. doi:10.1093/bjaceaccp/mks063 Retrieved from https://doi.org/10.1093/bjaceaccp/mks063

FLIR. (2004). ThermaCam Researcher Pro (Version 2.8 SR-1): FLIR Systems AB. Retrieved from www.flir.com

FLIR. (2013). *FLIR T620bx 25° (incl. Wi-Fi)*. Technical Data. Data sheet. FLIR Systems, Inc. Wilsonville, USA.

Fox, M., Coley, D., Goodhew, S., & Wilde, P. D. (2015). Time-lapse thermography for building defect detection. *Energy and Buildings, 92*(0), pp. 95-106. doi:http://dx.doi.org/10.1016/j.enbuild.2015.01.021 Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778815000274

Hart, J. M. (1990). An introduction to infra-red thermography for building surveys. *BRE Information Paper*(IP7/90)

Havenith, G. (2004). Thermal Conditions Measurement.

Hellgren, U.-M., Eero, P., Lahtinen, M., Henri, R., & Reijula, K. (2008). *Complaints and symptoms among hospital staff in relation to indoor air and the condition and need for repairs in hospital buildings*.

Hwang, R.-L., Lin, T.-P., Cheng, M.-J., & Chien, J.-H. (2007). Patient thermal comfort requirement for hospital environments in Taiwan. *Building and Environment, 42*(8), pp. 2980-2987. doi:https://doi.org/10.1016/j.buildenv.2006.07.035 Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132306002083

Insler, S. R., & Sessler, D. I. (2006). Perioperative thermoregulation and temperature monitoring. *Anesthesiol Clin, 24*(4), pp. 823-837.

ISO. (2005). Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (Vol. ISO 7730:2005): ISO/TC 159/SC 5 Ergonomics of the physical environment.

ITC. (2006). *Thermography Level 1 Course Manual* Stockholm Sweden: Infrared Technology Centre, FLIR systems AB.

Ivarsson, B., Kimblad, P. O., Sjöberg, T., & Larsson, S. (2002). *Patient reaction to cancelled or postponed heart operations*.

Khalid, W., Zaki, S. A., Rijal, H. B., & Yakub, F. (2019). Investigation of comfort temperature and thermal adaptation for patients and visitors in Malaysian hospitals. *Energy and Buildings, 183*, pp. 484-499. doi:https://doi.org/10.1016/j.enbuild.2018.11.019 Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778818319443

Khodakarami, J., & Nasrollahi, N. (2012). Thermal comfort in hospitals – A literature review. *Renewable and Sustainable Energy Reviews, 16*(6), pp. 4071-4077. doi:http://dx.doi.org/10.1016/j.rser.2012.03.054 Retrieved from http://www.sciencedirect.com/science/article/pii/S1364032112002377

Kurz, A., Sessler, D. I., Narzt, E., Lenhardt, R., & Lackner, F. (1995). Morphometric influences on intraoperative core temperature changes. *Anesth Analg, 80*(3), pp. 562-567.

Lawrence, I. D., Jayabal, S., & Pattabi, T. (2018). *Indoor air quality investigations in hospital patient room*.

Lenhardt, R., Marker, E., Goll, V., Tschernich, H., Kurz, A., Sessler, D. I., . . . Lackner, F. (1997). Mild intraoperative hypothermia prolongs postanesthetic recovery. *Anesthesiology, 87*(6), pp. 1318-1323.

Leslie, K., & Sessler, D. I. (2003). Perioperative hypothermia in the high-risk surgical patient. *Best Practice & Research Clinical Anaesthesiology, 17*(4), pp. 485-498. doi:http://dx.doi.org/10.1016/S1521-6896(03)00049-1 Retrieved from http://www.sciencedirect.com/science/article/pii/S1521689603000491

NICE. (2007). Inadvertent perioperative hypothermia: the management of inadvertent perioperative hypothermia in adults *NICE guideline* (Vol. Draft, October 2007): UK NICE (The National Institute for Health and Care Excellence).

NICE. (2018). *Hypothermia: prevention and management in adults having surgery* (Clinical guideline No. London UK: N. I. f. H. a. C. E. (NICE). https://www.nice.org.uk/guidance/CG65

Onset. (2015). HOBO® MX1101 Data Logger. Bourne, MA: Onset Computer Corporation.

Porthosp. (2012). Interprofessional Learning Unit 3: Managing Inadvertent Peri-operative Hypothermia: an exploration into local practices (Vol. Group Number: 54).

Pourshaghaghy, A., & Omidvari, M. (2012). Examination of thermal comfort in a hospital using PMV–PPD model. *Applied Ergonomics, 43*(6), pp. 1089-1095. doi:http://dx.doi.org/10.1016/j.apergo.2012.03.010 Retrieved from http://www.sciencedirect.com/science/article/pii/S0003687012000385

Romanzini, A. E., Carvalho, E. C. d., & Galvão, C. M. (2015). Delayed surgical recovery: a concept analysis. *Revista Brasileira de Enfermagem, Brasília, 68*, pp. 953-960. Retrieved from http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0034-71672015000500953&nrm=iso

Sheth, A. Z., Price, A. D., & Glass, J. (2010). A framework for refurbishment of health facilities.

Short, C. A., Lomas, K. J., Giridharan, R., & Fair, A. J. (2012). Building resilience to overheating into 1960's UK hospital buildings within the constraint of the national carbon reduction target: Adaptive strategies. *Building and Environment, 55*, pp. 73-95. doi:http://dx.doi.org/10.1016/j.buildenv.2012.02.031 Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132312000765

Skoog, J., Fransson, N., & Jagemar, L. (2005). Thermal environment in Swedish hospitals: Summer and winter measurements. *Energy and Buildings, 37*(8), pp. 872-877. doi:http://dx.doi.org/10.1016/j.enbuild.2004.11.003 Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778804003470

Skyview. (2018). Skylink Pro. The Weather site. Retrieved Date Accessed, 2018 from http://skylink-pro.com.

Tansey, E. A., & Johnson, C. D. (2015). Recent advances in thermoregulation. *Adv Physiol Educ, 39*(3), pp. 139-148. doi:10.1152/advan.00126.2014

Torossian, A., Van Gerven, E., Geertsen, K., Horn, B., Van de Velde, M., & Raeder, J. (2016). Active perioperative patient warming using a self-warming blanket (BARRIER EasyWarm) is superior to passive thermal insulation: a multinational, multicenter, randomized trial. *J Clin Anesth, 34*, pp. 547-554. doi:10.1016/j.jclinane.2016.06.030

van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all? *Indoor Air, 18*(3), pp. 182-201. doi:10.1111/j.1600-0668.2007.00516.x

Verheyen, J., Theys, N., Allonsius, L., & Descamps, F. (2011). Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility. *Building and Environment, 46*(5), pp. 1195-1204. doi:http://dx.doi.org/10.1016/j.buildenv.2010.12.014 Retrieved from http://www.sciencedirect.com/science/article/pii/S0360132310003665

Walker, N. J. (2004). *Volume one - Principles and Practice* Northampton, UK: BINDT.

Yau, Y. H., & Chew, B. T. (2009). Thermal comfort study of hospital workers in Malaysia. *Indoor Air, 19*(6), pp. 500-510. doi:10.1111/j.1600-0668.2009.00617.x